ULTRASONIC SYSTEM FOR AUTOMATIC DETECTION OF DISBONDS IN COMPOSITE TUBE JOINTS

Flávio Buiochi, fbuiochi@usp.br
Marcos de Sales Guerra Tsuzuki, mtsuzuki@usp.br
Marcelo Yassunori Matuda, marcelo.matuda@usp.br
Nicolas Perez, nico@fisica.edu.uy
Julio Cezar Adamowski, jcadamow@usp.br
Department of Mechatronic and Mechanical Systems Engineering / University of São Paulo
Av. Prof. Mello Moraes, 2231, 05.508-030, São Paulo, SP, Brazil

Sérgio Damasceno Soares, sdama@petrobras.com.br
CENPES / Petrobras Research Center
Av. Horácio Macedo, 950, 21.941-915, Rio de Janeiro, RJ, Brazil

Abstract. *This work presents the development of an ultrasonic system for inspecting adhesive joints, using the pulse-echo mode. In order to test the proposed system, a real pipe section made with fiberglass reinforced epoxy resin composite, purposely containing disbonds, was provided by PETROBRAS oil company. A mechanical structure embraces the tube, allowing for rotational and translational movements of the transducer along the outer surface of the joint. The ultrasound transducer was coupled to the joint by flowing tap water. Two step motors, one moving linearly and the other moving angularly, were controlled by a specifically developed hardware, which generates the control pulses and the trigger signal to synchronize the ultrasonic emission. The hardware was connected to a PC through an RS-232C interface, and a software was implemented to control the hardware through a based protocol. Ultrasonic pulses are emitted, received and amplified using a pulser/receiver. An A/D converter board was plugged into the PC and the software controled the acquisition. It is possible to observe the acquired signals in A-, B- and C-scans using the visualization software. Tests were carried out by using a 2-MHz ultrasonic transducer to inspect four joints. In order to verify the capability of detecting defects at poor resolutions, C-scan images were acquired using three different spatial discretizations (2, 4 and 6 mm). Moreover, for comparison purposes, a 5-MHz ultrasonic transducer was used to inspect one of those joints. This higher frequency transducer results in higher resolution. However, the smaller attenuation at 2 MHz makes it easier to find returning echoes, especially when dealing with the composite, which is an extremely lossy material. The ultrasonic technique has viability to inspect adhesive joints since it was capable of detecting the inserted defects.*

Keywords*: ultrasonic inspection, composite tubes, nondestructive testing*

1. INTRODUCTION

Composite is an interesting alternative to steel used on water pipes in the oil industry. The composite is constituted of epoxy resin matrix and fiberglass reinforcement. It is a light material with high mechanical strength and corrosion resistance. Composite pipes are built by bonding adjacent cylindrical composite parts, using adhesively bonded joints, which are vulnerable to flaws, such as disbonds (voids). Disbonds can occur during the manufacture due to the presence of contaminants (such as oil, grease) on the adherent surface prior to bonding, or can also occur after the construction process, as a result of impact or environmental degradation of adhesive joints (Adams and Drinkwater, 1997). Aiming to detect disbonds, a widespread problem in composite pipes, the oil industry is endeavoring to find effective nondestructive testing methods. The successful use of composite pipes depends on the technique applied for flaw detection. In this sense, studies are being conducted using the following techniques: shearography, thermography and ultrasound (Willemann *et al.*, 2010).

A shearography system is an optical technique used to evaluate the integrity of structures and mechanical components. To use this technique it is necessary to apply an initial load on the test object, and through analysis of deformation fields of the object surface, it is possible to identify the presence or absence of internal flaws. However, there is still much to be studied, because according to the applied loads (thermal, internal pressure, vacuum and vibration), different behaviors are observed due to the presence of flaws (Schontag, 2009). The work of Willemann *et al.* (2010) presents the results obtained with the optical shearografy technique during inspection of adhesively-bonded joints. For analyzing composite joints, the pipes were submitted to a differential internal pressure, creating a relatively uniform deformation field in the absence of defects, and varying the fringe patterns in the presence of bond failures. The authors concluded that the visual identification of such patterns still depends on experienced operators, and that the severity of the defect cannot yet be evaluated upon observing fringe interference (Willemann et al., 2010).

An active thermography system is another technique applied to detect flaws in composite materials. Defects can be detected by heating one surface of a bonded structure and measuring the transient thermal response during heating and/or cooling stages. Areas of disbond are resistant to the transfer of heat. It is a non-contact technique capable of inspecting a relatively large area quickly (Adams and Drinkwater, 1997) (Schroeder *et al.*, 2002). Willemann *et al.* (2010) used this technique to inspect joints of composite pipes, by heating the surface of the joint with a halogenous light bulb and then monitoring the cooling with an infrared camera. However, the authors state that in this first stage of their study, the technique performance was dependent on sample size, location of defects and existence of surface features that may influence the heat flow (Willemann et al., 2010).

The ultrasonic inspection technique is one of the most widely used methods of nondestructive testing. In this case, the ultrasonic technique proposed is based on the pulse-echo mode, in which a single transducer is responsible for both transmitting and receiving ultrasonic waves that propagate in the material. The transducer is usually separated from the test piece by a couplant (such as oil, grease, and commercial gel) or by water, as in immersion testing. The acquired RF (radio frequency) signal represents the ultrasonic reflected waveforms that come from the interfaces, such as the test piece walls, or from discontinuities (or flaws) inside the object. It is possible to determine the position of the discontinuity along the ultrasound beam inside the part. The distance is calculated from the difference between the times of arrival of the echoes, e.g., reflected from the interface and the flaw, multiplied by the ultrasonic propagation velocity in the inspected medium. The envelope of the RF rectified signal can be displayed as a function of time (or distance) in what is called an A-scan signal, where “A” means amplitude (Krautkrämer and Krautkrämer, 1990).

A two-dimensional ultrasonic image can be formed by the collection of A-scan signals obtained by mechanically displacing a single-element transducer or even electronically steering an array transducer. The recorded data can be visualized as a cross-sectional view of the piece, with each trace corresponding to an ultrasonic transducer position (in case of a single-element transducer). The brightness of the pixel in each trace on the image is proportional to the amplitude of the received echo envelope. Such an image is called a B-scan, where “B” denotes brightness (Fatemi and Kak, 1980).

Another image, known as a C-scan, can also be obtained by moving the single-element ultrasonic transducer in a raster pattern over the surface of the test piece, using the pulse-echo technique (Krautkrämer and Krautkrämer, 1990). This can also be done by mechanically displacing an array transducer in one direction. The C-scan image is performed by measuring the echo amplitude in a temporal gate of the recorded A-scan signal for every scanning position. Changes in the echo amplitude show the presence of discontinuities from the internal region of the test piece. The gate width is properly adjusted in order to inspect the regions of interest such as the bonded parts of an adhesive joint. Such images are of great importance in ultrasonic inspections, because it plots a map of the defects over the scanning area.

The ultrasonic pulse echoes reflected from fiberglass-reinforced polymer materials are always corrupted by spurious signals generated by the structure of these materials. To ensure a reliable and repetitive inspection, a computerized device can be used for automatic scanning the outer surface of the joint. This allows accurate movement of the ultrasound transducer without changing the distance and/or inclination relative to the irregular surface of the tube. Furthermore, the scan should be performed in the shortest time possible, not only due to the large number of joints to be inspected, but mainly because the production stops for the inspection. A computerized device that performs the scan with an ultrasonic transducer was developed to automatically inspect the external surface of adhesively-bonded joints.

2. DESCRIPTION OF THE ULTRASONIC SYSTEM

2.1. Mechanical scanning device

Figure 1 shows the mechanical device attached to the composite tube. It is composed by a mechanical structure that embraces the tube, allowing for rotational and translational movements of the ultrasonic transducer along the outer surface of the joint. The transducer rotates through a pair of cylindrical spur gears (ratio equals 14), with the crown fixed to the structure that holds the tube and pinion driven by a stepper motor. A circular motion guide allows precise positioning of the head along the circumference of the tube. The crown and circular guide are split structures that embrace the tube. The axial scan is performed by a linear drive mechanism comprising a linear guide and a lead screw (5-mm pitch) with recirculating ball nut, also driven by a stepper motor. The two 4-phase stepper motors are driven by micro-step driver (2000 steps per revolution). The resolutions of linear and rotational motions are, correspondingly, 0.003 mm and 0.02mm.

The ultrasonic transducer was chosen based on the axial resolution and on the acoustic attenuation allowed for the application. The greater the transducer frequency, the shorter is the wavelength, and therefore the better is the axial resolution. However, the acoustic attenuation increases with frequency. So, a 2-MHz ultrasonic transducer was selected, providing a good compromise between axial resolution and attenuation for this application. Furthermore, a 5-MHz transducer was used for comparison purposes, despite the high attenuation. Both ultrasound transducers used were broadband and with a 10-mm diameter.

A flowing tap water, supplied through a hose, was used as ultrasonic couplant between the transducer and the outer wall of the joint. This type of coupling was found to overcome the roughness of the tube surface. The ultrasound propagates along a moving column of water, which is limited to a conical acrylic housing. The acrylic was chosen as the housing material because it allows visualizing through the chamber, and so the existence of bubbles can be monitored and avoided. The chamber through which the water flows has a truncated cone geometry. The section of smaller area is used as the water output to increase pressure loss, thus avoiding a fast runoff and hence the appearance of air bubbles that interfere in the ultrasound inspection. Moreover, the chamber is compressed against the tube surface to help holding the water and keeping the contact while scanning. The compression force is adjusted by a couple of springs.

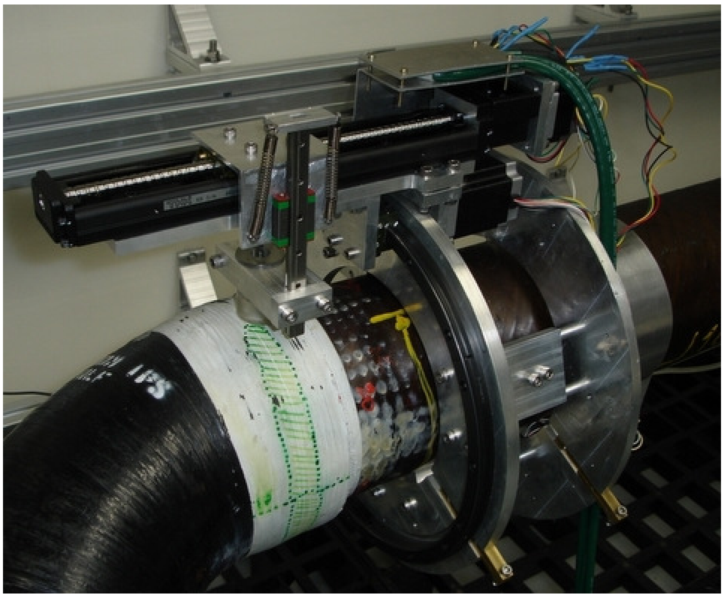

Figure 1. Mechanical parts of the automatic ultrasonic inspection system embracing the pipe.

2.2. Electronic Hardware

Figure 2 shows the block diagram of the automatic ultrasonic inspection system, which is composed by a microcomputer that controls the digital acquisition board and the scanning hardware. The scanning hardware consists of a Rabbit BL1800 microprocessor that drives the scanning device and generates the trigger to start the transducer operation and signal acquisition. The microprocessor is connected to the computer via an RS-232C interface.

The ultrasound transducer is excited with a narrow pulse (broadband), generated by the model 5077PR Ultrasonic Analyzer (Panametrics-NDT, Olympus), which also receives the signals with up to 60dB gain. The signal acquisition is made with an analog to digital (A/D) converter board (NI-DAQ Driver) with 50 MHz sampling rate and 12 bit resolution for the amplitude measurement. This board is placed in one of the slots in the PC bus and its main advantage is a faster signal acquisition, an important factor when scans are performed with a large number of points. The stored signals are processed and presented to the user through a graphical interface.

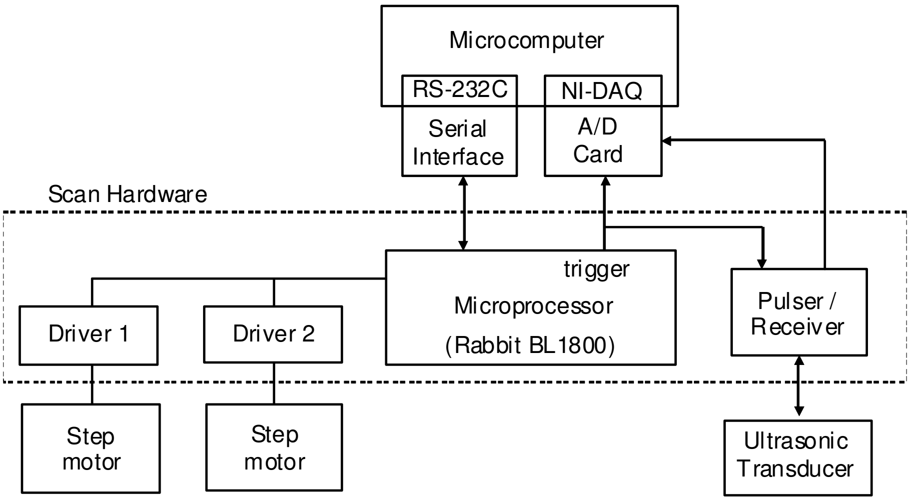

Figure 2. Block diagram of the automatic inspection equipment.

2.3. Control Software

The control software was implemented in C++ for Windows. Its function is to integrate the scanning hardware and the digital signal acquisition board, automating the transducer positioning, excitation and reception processes. When this software runs for the first time, a register is created on Windows, generating a folder for storing the scanned signals. The user can program the inspection, defining the scanning and the acquisition parameters. The scan control software has three windows for selection of settings (scan setup, signal preview and scanning window).

The scan setup window, shown in Fig. 3, allows setting the serial port used for communication, the sampling rate (usually 50 MHz), and the logical device (acquisition board). These settings must be made before using the software. In addition, the directory where the scan will be stored can be selected, and the transducer can be moved to the specific place to be inspected.

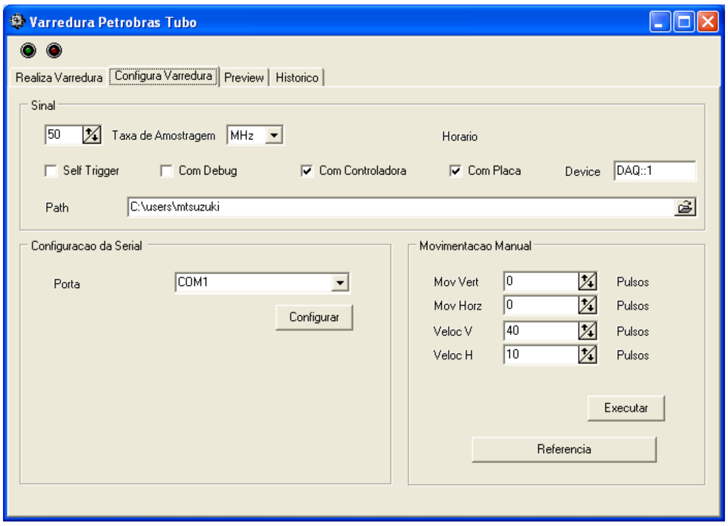

Figure 3. Scan setup window.

The signal preview window, as shown in Fig. 4, allows to adjust the acquisition parameters (acquisition window, the maximum amplitude of the signal, trigger level, etc.) for configurating the NI-DAQ acquisition board. The parameter “range” sets the scale of the A/D converter in volts for the acquisition, the maximum fixed value in this range corresponds to 127 and the minimum value is -127, that is, an 8-bit resolution. The acquisition window refers to the interval between the beginning and the end of acquisition. This interval is defined by the parameters “delay”, “number of points”, and “sampling rate”, where the first parameter allows delaying the acquisition with respect to the trigger, the second indicates the number of points stored in each acquisition, and the third was defined previously in the scan setup window (Fig. 3). The parameter “timeout” indicates the maximum time to wait for a trigger signal without error, and the parameter “trigger level” indicates the magnitude of the trigger signal in volts. Before starting a scan, it is appropriate to confirm if the acquisition is being done correctly. Thus, one should visualize the signal by clicking on the "execute" button. The button "abort" can be selected any time to stop the visualization.

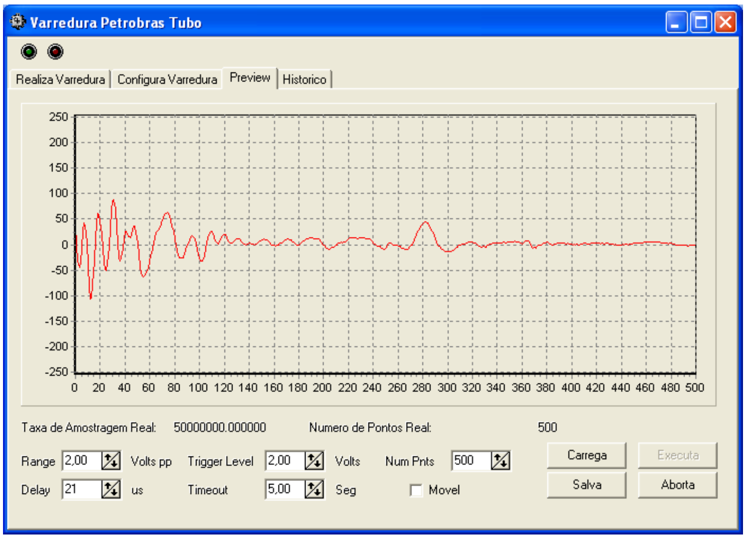

Figure 4. Signal preview window.

Figure 5 presents the scanning window, where the user can select the region of inspection, set the resolution and control the scan velocity in two directions (axial and circumferential). The axial direction refers to the pipeline axis, and the circumferential direction refers to the pipeline radial direction. The implemented version allows the selection of the number of points, both in axial and circumferential direction, and the number of pulses to be delivered for each scan. The folder where the scanned signals are kept is also defined on this window. Once the scan and acquisition parameters are set, the system scans the pre-defined area. The scan performed by the control software is completely automatic, and the data is stored in files. The ultrasonic transducer is moved in a raster pattern, in which the test piece is scanned from side to side in lines from top to bottom.

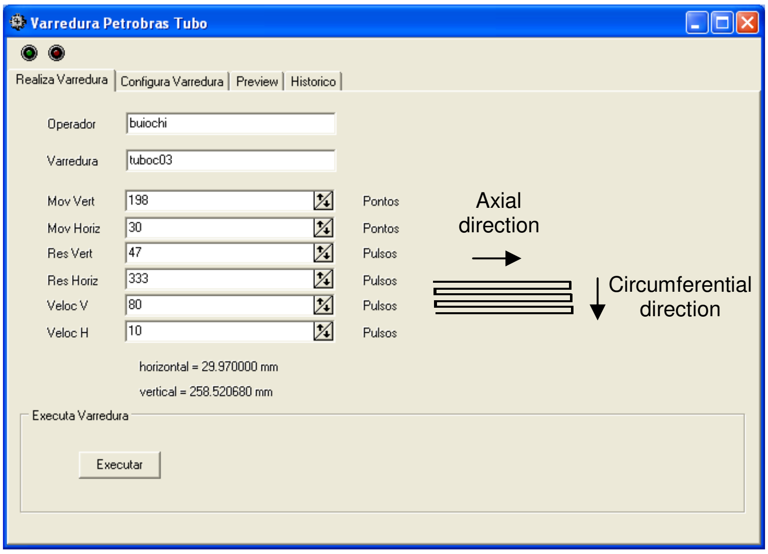

Figure 5. Scanning window.

Finally, the collected A-scan data from each scanned position is integrally stored on the hard disk. The scan reading is done by the visualization software written in C++ for Windows. Figure 6 shows the scanning display software window with four main images. The top image displays the entire scan area of the joint in C-scan image. The image intensity is defined by the signal of greater magnitude within the limits defined in the A-scan signal (bottom image). The image just below the top image presents the temporal signals obtained from the horizontal line (axial direction), that is, the B-scan image. The image on the right side represents temporal signals obtained in the vertical line (circumferential direction). The bottom image is the A-scan, representing the ultrasonic signal obtained at the intersection of horizontal and vertical lines represented in C-scan.

In addition to the preview window, there are two other windows that allow color and boundary settings. The color setting assists the scan interpretation. The software allows inserting, modifying and removing colors for representing different intensity levels. Since the boundary settings can consider complex geometries, where the signal cannot be directly observed due to multiple reflections, a time window can be applied to the region of interest in order to obtain a C-scan image preview. On Figure 6, two vertical lines drawn on the A-scan signal indicate the limits used for calculating the C-scan image. The maximum amplitude of each A-scan signal is used for defining the colors of the C-scan image.

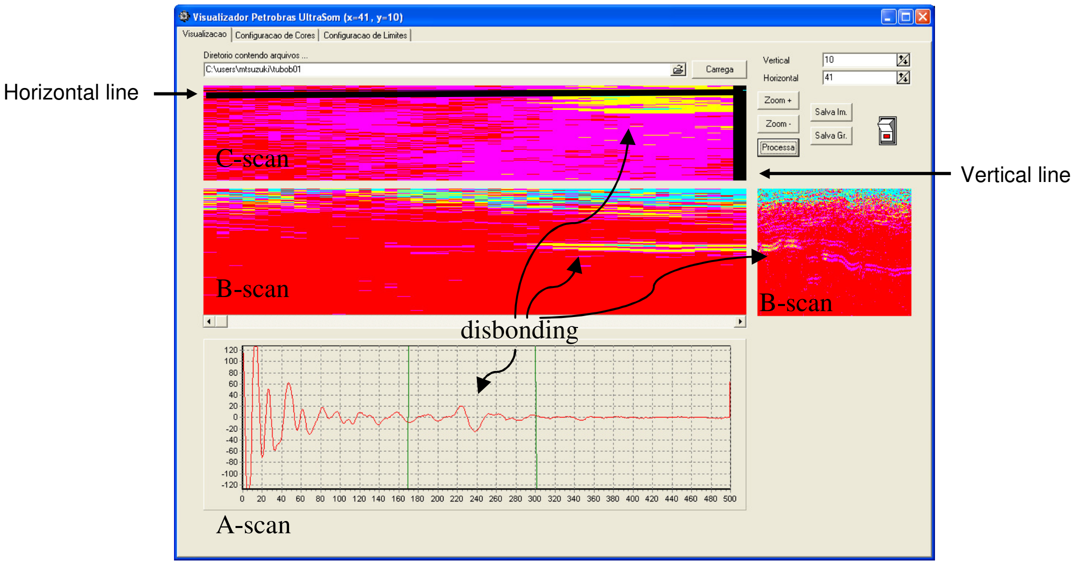

Figure 6. Scanning display software window.

The detection of a real disbond in adhesive joints is presented in Fig. 6, as shown in C-scan and B-scan images. For the A-scan signal, there is an echo within the time window defined by the limits of the vertical lines. Since in this example, there was an echo in this time window, this signal depicts a disbond. Otherwise, if there was no echo in the time window, there would not exist any defect. The position of the defect can be calculated from measuring the time elapsed between the outer wall echo and the echo resulting from the detachment of the board, as long as the propagation velocity of the acoustic wave in the composite material is known.

3. EXPERIMENTAL RESULTS

Figure 7 shows a test piece built with composite (fiberglass-reinforced epoxy resin) tubes and curves of 6-inch nominal diameter. It contains four joints (J1, J2, J3 and J4) bonded by epoxy resin. During the assembly, which was done at CENPES/PETROBRAS, artificial defects were created in the joints.

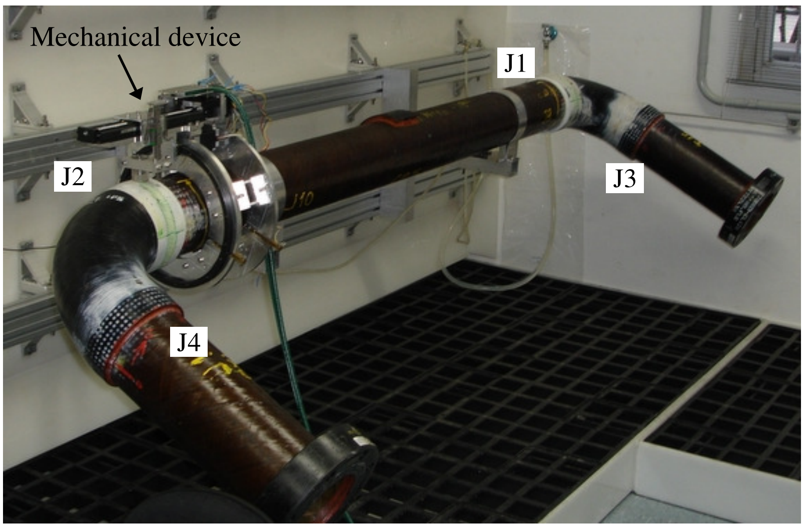

Figure 7. Experimental configuration (mechanical device attached to the composite tube with 4 joints)

The inspection equipment operation was preliminarily tested using a 2-MHz 10-mm-diameter ultrasonic transducer. For each joint, the tests were repeated three times using different spatial discretizations (2, 4 and 6 mm). The capability of detecting defects at poor resolutions was verified on C-scan image results. Figure 8 presents the C-scans obtained from joint J1, changing the spatial discretization. The presence of defects is indicated by a circle, and can be confirmed by knowing their real positions, since they can be visually detected in the case of joint J1. The defects are two small horizontal holes in the epoxy resin layer.

The inspection time of a joint depends on the scanning resolution and on the speed of transducer displacement. For the raster scans performed over the entire surface of the joint J1, shown in Figure 8, the times were 58, 25 and 16 minutes, respectively, for the resolutions of 2, 4 and 6 mm.

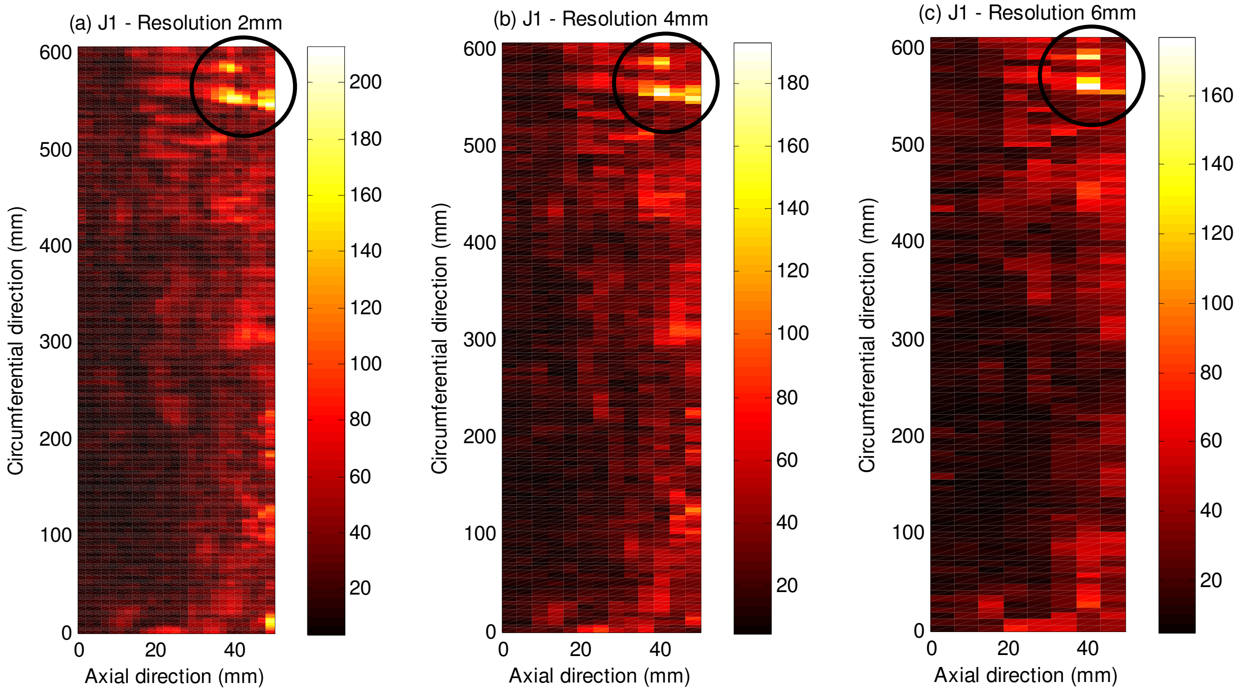

Figure 8. Comparison of the C-scan images from joint J1 obtained using the 2-MHz transducer for three different spatial resolutions: (a) 2 mm, (b) 4 mm, and (c) 6 mm.

Figure 9 shows the C-scan images from joints J2, J3, and J4, using a 4-mm spatial resolution and a 2-MHz 10-mm-diameter ultrasonic transducer. Figure 10 shows the comparison of C-scan images obtained from joint J2 with two transducers (2 MHz and 5 MHz), considering a 2-mm spatial resolution. As a good axial resolution was obtained for both frequencies, the lower frequency transducer can be chosen for inspection. At 2 MHz, the attenuation is smaller, leading to a higher penetration and to reflected echoes of greater magnitude.

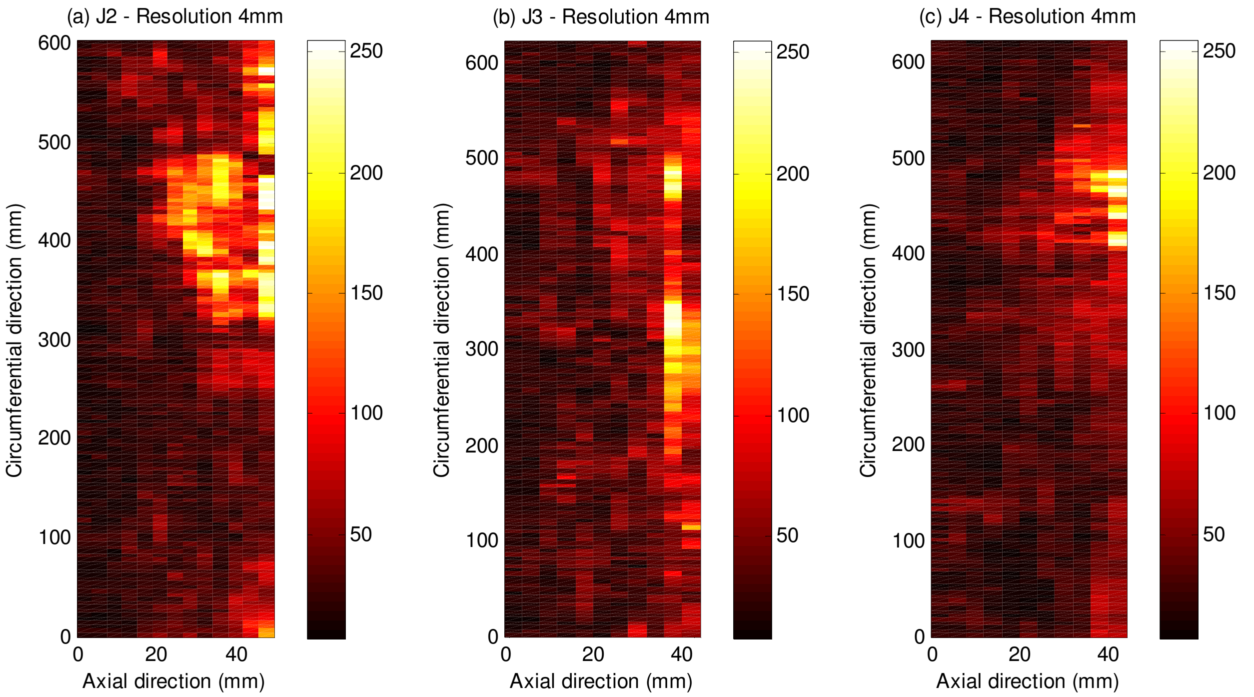

Figure 9. C-scan images obtained from joints (a) J2, (b) J3, and (c) J4 at 4-mm spatial resolution, using the 2-MHz transducer.

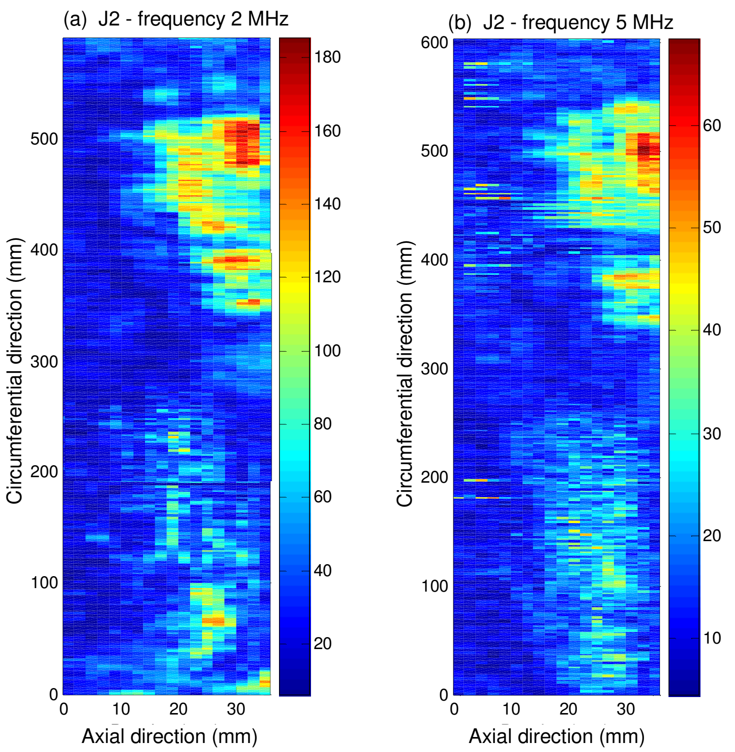

Figure 10. Comparison of the C-scan images from joint J2 at 2-mm spatial resolution obtained for two frequencies: (a) 2 MHz, and (b) 5 MHz.

4. CONCLUSION

An automated disbond inspection system using an ultrasonic transducer was developed. It is aimed at detecting disbonds of adhesive joints, using normal incidence ultrasonic measurements. Experimental measurements were performed with two ultrasonic transducers (2 and 5 MHz). It is known that higher frequencies increase the axial resolution, but the signals are more attenuated. It was found that the lower frequency transducer should be used for inspection due to the smaller attenuation.

Since the composite is a fiberglass-reinforced epoxy resin, it is a highly attenuating material and generates multiple reflections. When the inspection system is assembled directly in the composite pipe, there is a need to adjust the temporal gate and the gain in terms of the location and degree of disbond. To overcome this difficulty, it is important to previously calibrate the system. This can be done by using a calibration block made of the same material and using the same thickness of the pipe.

The system is capable of plotting a map of disbonds (C-scan image) of the adhesive interface. The C-scan results indicate the existence of defects in all joints. However, for verification purposes, the destructive analysis of the joints should still be performed. Meanwhile, the results of the C-scan performed for joint J1 can be validated by the real location of the defect that is externally visible in joint J1. Therefore, the ultrasonic system proved capable of accurately defining the position of joint defects.

The ultrasonic inspection system presented a good repeatability, even when applying different spatial discretizations. The results of the various tests carried out in this study show that the ultrasonic inspection technique is a reliable one. At this point, the experiments are being conducted inside the laboratory, as some adjustments must be done to conclude the equipment development. Once it is ready, it will hopefully be applied to inspect joints in the oil industry. One of the advantages of this nondestructive ultrasonic equipment is the cost of implementation, which is lower than that of other methods.

5. ACKNOWLEDGMENTS

The authors would like to thank PETROBRAS/ANP, FAPESP and CAPES for the financial support that made this work possible.

6. REFERENCES

Adams, R. D. and Drinkwater, B. W., 1997, “Nondestructive testing of adhesively-bonded joints”, NDT & International, Vol. 30, No. 2, pp. 93-98.

Fatemi, M. and Kak, A.C., 1980, “Ultrasonic B-scan imaging: Theory of image formation and a technique for restoration”, Ultrasonic Imaging, Vol. 2, pp. 1-47.

Krautkrämer, J. and Krautkrämer, H., 1990. “Ultrasonic Testing of Materials”, Springer-Verlag, Fourth Edition, New York.

Schontag, J. M., 2009. “Caracterização da profundidade de defeitos em materiais compósitos utilizando shearografia com carregamento vibracional”, dissertação de mestrado, Universidade Federal de Santa Catarina, Florianópolis-SC.

Schroeder, J.A. Ahmed, T., Chaudhry, B. and Shepard, S., 2002, “Non-destructive testing of structural composites and adhesively bonded composite joints: pulsed thermography”, Composites: Part A, Vol. 33, pp. 1511-1517.

Willemann, D.P., Marinho, C.A., Soares, D.S., Albertazzi, A., Daniel, P.C.F., Hofmann, H.B., Schweitzer, L.G., 2010, “Detecção de defeitos em juntas adesivadas de tubos compósitos com shearografia, termografia e ultrassom”, Revista Abendi Especial – Guia de Ensaios Não Destrutivos e Inspeção, No. 40, pp. 80-86.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.